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RADIATION DETECTORS AS SURVEILLANCE MONITORS*

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ABSTRACT

The International Atomic Energy Agency (IAEA) proposes to use personnel dosimetry radiation detectors as surveillance monitors for safeguards purposes. It plans to place these YES/NO monitors at barrier penetration points declared closed under IAEA safeguards to detect the passage of plutonium-bearing nuclear material, usually spent fuel. For this application, we surveyed commercially available dosimeters as well as other radiation detectors that appeared suitable and likely to be marketed in the near future. We found no primary advantage in a particular detector type because in this application backgrounds vary during long counting intervals. Secondary considerations specify that the monitor be inexpensive and easy to tamper-proof, interrogate, and maintain. On this basis we selected radiophotoluminescent, thermoluminescent, and electronic dosimeters as possible routine monitors; the latter two may prove useful for data-base acquisition.

INTRODUCTION

For unattended surveillance of barrier penetrations, the IAEA currently uses Toshiba** glass radiation dosimeters*** enclosed in a metal seal to detect undeclared movement of safeguarded nuclear material, especially irradiated fuel elements. The glass radiophotoluminescent (RPL) dosimeters are

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**Toshiba Glass Co., Ltd., Tokyo, Japan.

***Mention of specific commercial products in this paper does not constitute an endorsement by the Los Alamos National Laboratory, University of California.

simple, compact, low cost, and tamper-indicating (when used in a seal). Because these dosimeters may no longer be available in the future, the IAEA authorized us, under the U.S. Program for Technical Assistance to IAEA Safeguards, to evaluate alternative candidates.

SURVELLIANCE MONITORING

Surveillance monitoring for IAEA safeguards requires that a monitor be easily installed, retrieved, and read, and that it survive long periods (up to one year) of operation without maintenance or external power. Thus, passive, solid state, or chemical dosimeters have a distinct advantage over others, such as electronic dosimeters, that require line power. At present, monitors do not record a time-history during operation, but simply integrate data for an entire monitoring period.

In a surveillance monitor, the criterion for detecting diversion is to compare a monitoring period measurement with a level derived from previous experience under background conditions. The optimal choice for setting an alarm level uses the maximum average background expected at a location plus an increment that is large enough to provide an acceptably low false alarm rate. The level should be well above the mean, perhaps by as much as a factor of five, as Schaer[1] recommends in his evaluation of RPL monitors. In any event, the detection criterion will be that the incoming signal plus the normal background must exceed some multiple of the expected background.

We examined the impact of radiation detectors on monitor performance by looking more closely at the detection criterion. Denoting the detected signal during a diversion by S, the background for the monitoring period by B, and a multiplier used to determine the alarm level by M, an alarm condition exists when

$$S + B \geq MB \quad .$$

In terms of the passage parameters v for velocity, r_0 for distance of closest approach, and the source term S_0 (detected count rate at a 1-m distance), the detected signal S during passage at uniform velocity is

$$S = \frac{\pi S_0}{r_0 v} \quad .$$

Substituting for S, we can state the minimum detection criterion as

$$\frac{\pi S_0}{r_0 v} + B = MB \quad .$$

Solving for the detection range r_0, we have

$$r_0 = \frac{\pi S_0}{vB(M-1)} \quad .$$

The detection range is useful as a measure of performance; the monitor with the highest detection range is best. The range improves when the velocity decreases, when the multiple of background decreases, or when changes in detectors are made that increase the signal without corresponding increases in background. In general, an increase in detector efficiency has no beneficial effect because it increases background and signal by the same factor. This result is in sharp contrast to other safeguards monitor requirements where the background is well known, or its history is followed, allowing an alarm level derived from the standard deviation to be used.

Background-following monitors signal a diversion when a current measurement exceeds a continuously updated background count by a multiple of the standard deviation of the background. The alarm condition can be stated as

$$S + B \geq B + MB^{1/2} \quad .$$

When the monitor sample interval is long enough to detect a diversion in a single count, has no beneficial effect because it increases background and signal by the same factor. This result is in sharp contrast to other safeguards monitor requirements where the background is well known, or its history is followed, allowing an alarm level derived from the standard deviation to be used.

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When the monitor sample interval is long enough to detect a diversion in a single count, the detected signal is again

$$\frac{\pi S_0}{r_0 v}$$

and the detection range is

$$r_0 = \frac{\pi S_0}{v M B^{1/2}} \quad .$$

In this case there is an advantage in choosing the highest efficiency detector because improvement to detector efficiency extends the detection range even though signal and background increase in the same proportion. We conclude that for long term surveillance monitoring where background following logic or long term recording of data is not used, the efficiency of one detector relative to another is not an important selection criteria.

The choice of detecting gamma rays or neutron radiation depends on the type of detection logic to be used and detailed knowledge of background and source emission spectra. Comparative measurements are needed in specific cases, but, in general, it is the predominant gamma-ray emissions from irradiated fuel that the IAEA needs to detect.

RADIATION DETECTORS

With no clear optimization goal to restrict our search, we looked at all of the commercially available personnel dosimeters that seemed suitable for a year long, unattended monitoring period and that were compact, simple, low-cost, and tamper-indicating. In the process we found a few dosimeters with uniquely attractive characteristics that seemed to be nearing commercial availability and included them in our survey.

We began the survey by examining the RPL dosimeters and proceeded to look at thermoluminescent dosimeters, film badges and ion chambers, photochemical dosimeters, superheated drop detectors, electronic pocket dosimeters, and other detectors. A brief description of each dosimeter or detector type and how it meets the requirements for surveillance monitoring follows.

Radiophotoluminescent Dosimeters

The IAEA's present surveillance monitoring technique uses RPL dosimeters that luminesce under ultraviolet (uv) radiation after exposure to ionizing radiation.[2] Absorption bands in the near uv range are formed during irradiation; during readout interrogation, illumination in that band produces luminescence proportional to the irradiation dose. The readout process does not destroy the absorption bands, thus, repeated readings may be used to verify an initial reading or to increase the precision of the readout result.

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Other advantages of the RPL dosimeter are its small size relative to other dosimeters (Fig. 1), lack of power requirements, ease of tamper-proofing, and relative freedom from signal fading. The RPL dosimeter is sensitive to gamma radiation and can be made neutron sensitive when used with external converters or internal absorbers or scatterers.

The major drawback to RPL dosimeters is that there is no longer a commercial supplier. [illegible] supplied readers and dosimeters at one time but is not [illegible] now. There are other drawbacks: RPL dosimeters can be erased using heat or uv radiation; moreover, their small size makes it easy to shield them from radiation during a diversion.

Thermoluminescent Dosimeter

Radiothermoluminescent (TLD) dosimeters trap energy in metastable states during irradiation; light is emitted when the trapped energy is released by heat during the reading process.[3] Many materials display thermoluminescence. Commercial dosimeters commonly use LiF or CaF that contain activators. Lithium-fluoride may be used for gamma-ray or neutron dosimetry. Neutron dosimetry is carried out by comparing calibrated natural LiF chips with ^{7}LiF chips, which have negligible neutron sensitivity. Lithium-fluoride dosimeters can either be purchased directly or provided by a dosimetry service.

TLDs are small, which makes them easy to tamper-proof and permits multiple chips to be used for precision or reliability. The dosimeters require no power, are inexpensive, and can be provided by a dosimetry service, which reduces the cost of monitoring. TLD dosimeters have two major drawbacks: latent exposures are erased by heat and their smallness makes it easy to shield them from radiation during a diversion.

Film Badges and Ion Chambers

Common personnel dosimeters based on photographic film and electrostatic charge collection are unsuitable for the IAEA application for a number of reasons.[4] Charge leakage limits the ion chamber to short duration measurements. Film is expensive, requires an inordinate amount of time and effort to read, is not reusable, and blackens on exposure to light, extreme heat, pressure, and chemicals. Moreover, the latent image fading rate increases in a warm humid environment, such as would be the case for irradiated fuel surveillance.

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Photochemical Dosimeters

Photochemical dosimeters are practical for surveillance monitoring in the form of paper or sheets impregnated with colorless precursors of a highly colored, stable organic dye.[5] These are relatively high level dosimeters; those now available have a threshold of perhaps 5×10^4 R. They can be used wherever the signal is large, for example, from recently irradiated fuel. Thicker photochemical dosimeters with a lower threshold would improve their usefulness for the IAEA application.

Photochemical dosimeters have the advantages of small size, low cost, and the capability of [illegible] more than once. Their drawbacks are that they are destroyed by exposure to light or heat, are easily shielded because of their small size, and are not reusable.

Superheated Drop Detectors

A new technique that may apply to surveillance monitoring uses bubble chamber principles.[5] Small superheated drops are dispersed and immobilized in a gel host medium. Radiation-induced nucleation destroys only the superheated drop in which it occurs. The total amount of vapor released from a gel packet is a measure of the radiation exposure and can be determined from the packet density. The dosimeter senses fast neutrons (1-10 MeV) and gamma rays above 6 MeV, making it suitable for monitoring irradiated fuel that has been freshly discharged.

Superheated drop detectors (SSDs) have potentially low background because they are only sensitive to energetic radiation. Other advantages are: they require no power, can be easily read out, are difficult to shield because of high energy neutron and gamma-ray sensitivity, can be read serially at selected intervals, and have selective sensitivity to freshly irradiated fuel. Anticipated drawbacks are their sensitivity to heat, to mechanical disturbances, and to outgassing of the host gel medium.

Electronic Pocket Dosimeters

Pocket dosimeter and electronic-film badge are terms that apply to small battery-operated radiation instruments used to measure and announce the presence of a certain dose or dose rate of gamma radiation.[7,8] Currently, they are used to detect potentially dangerous radiation fields or to act as timely personnel dosimeters in lower dose rate situations.

Pocket dosimeters basically consist of a radiation detector; electronic circuitry to detect and accumulate dose increments; a display mechanism; and a small, sometimes rechargeable, battery power source. A Geiger-Mueller (GM) tube is the common radiation detector used in pocket dosimetry because it is small, simple,

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Pocket dosimeters basically consist of a radiation detector; electronic circuitry to detect and accumulate dose increments; a display mechanism; and a small, sometimes rechargeable, battery power source. A Geiger-Mueller (GM) tube is the common radiation detector used in pocket dosimetry because it is small, simple, inexpensive, and has modest power requirements. The GM counter response mimics tissue dose response by means of thin lead shielding that reduces its inordinately high sensitivity to low energy photons. Power requirements for pocket dosimeters can be minimized by using low power CMOS (complementary metal-oxide semiconductor) circuitry and a power supply that only functions when needed. Manufacturers have claimed a six-month lifetime for alkaline batteries in low power dosimeters, however, deployment in such claims is only [illegible] hours out of a 24-hour day. A [illegible] of battery characteristics (Table I) [illegible] battery with a slightly larger volume could provide year-long operation. Rechargeable batteries could be used, but if they are constantly charged without periodic deep discharge they can become conditioned and fail to supply higher levels of power when it is needed.

We have described in detail the characteristics of commercial pocket dosimeters elsewhere.[10] The general characteristics that make electronic dosimeters good candidates for surveillance monitoring are that they are relatively inexpensive, little affected by environmental hazards, easy to read, immune to dose buildup or decay, and reusable. The main hazard to electronic dosimeters is damage to circuit boards caused by mechanical shock, salt, or corrosive atmosphere.[11] Battery failure can cause loss of data unless a separate backup battery for preserving memory is used. Microphonic noise and occasional noisy detectors are other drawbacks in long term monitoring with pocket dosimeters.

Alternative Detectors

Other possibilities for IAEA surveillance monitoring are more elaborate electronic nuclear radiation monitors and thermal radiation detectors. Infrared heat sensors are available in small, inexpensive units that include detection logic.[12] These could be used with additional recording circuitry to detect the passage of recently discharged irradiated fuel at high temperatures.

More elaborate electronic monitors have been developed for IAEA monitoring applications where a time-history of radiation intensity is desired.[13] Such a time-history could be used for more sensitive surveillance monitoring where high count rates that result from diversion would appear in the data against the background at the time. It is possible to detect shielding of this type of monitor by a relative decrease in the recorded count rate. This method for recording time-histories could be implemented by designing an instrument similar to the pocket dosimeter but

Characteristics of the dosimeters we have investigated appear in Table II. At present there seems to be no advantage to replacing the RPL dosimeters for IAEA surveillance monitoring, except that continued commercial availability of the dosimeters is not assured. TLD dosimeters are a reasonable alternative, particularly if a dosimetry service is used, which would eliminate the need to read the dosimeters at the IAEA headquarters. Another alternative is electronic dosimeters, but they would involve a larger initial expense than TLDs and require a reasonably large maintenance effort.

Surveillance monitoring could be improved by the development of an instrument that records a time-history or that electronically follows background and detects significant changes. In this case it is important to select a sensitive detector such as sodium-iodide or bismuth-germanate ($Bi_4Ge_3O_{12}$).

Development of a new instrument for IAEA surveillance monitoring requires more comprehensive information about signals and background, which can only be gained by experience. Such a data base could easily be constructed from measurements with TLD or electronic dosimeters.

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TABLE I

CHARACTERISTICS OF COMMON BATTERIES

Battery	Cell Open-Circuit Voltage (V)	Energy Density ($W \cdot h/16\ cm^3$)	Storage Life at 20°C (years)	Low Temperature Performance	Shape of Discharge Curve
Zinc-carbon	1.5	2	1-2	poor	sloping
Alkaline	1.5	3	2-4	good	sloping
Mercury	1.35	6	3-4	poor	flat
Lithium	2.95	8-13	10+	excellent	flat
Nickel-cadmium	1.2	1.7	1 (mo)	good[a]	flat

[a]Poor at high temperature.

Dosimeter Type	Commerical Availability	Reuse	Radiation Detected	Range Dose (R)	Readout Means	Fading
RPL	questionable	yes	gamma	$10^{-3} - 10^{3}$	reader	slight
TLD	yes	yes	gamma/neutron	$10^{-3} - 10^{5}$	reader	moderate
Ion Chamber	yes	yes	gamma	---	---	high
Photo-chemical	yes	no	gamma	$10^{-3} - 10^{7}$	reader	questionable
Superheated Drop	research	no	neutron	---	self	---
Electronic	yes	yes	gamma	$10^{-3} - 1$	self or reader	none
Large Electronic	research	yes	gamma/neutron	---	strip chart	none

Thermal Effects	Optical Effects	Mechanical Effects	Power Requirement	Advantages	Drawbacks
above 400°C	data loss	surface abrasion	no	small, no power, fits in seal	unavailable, read at IAEA, shieldable
above 240°C	increased exposure	---	no	commercial service, small, no power	thermal erasure, shieldable
---	no	damage	no	easily read	leakage
data loss	yes	---	no	high exposure range	shieldable
nucleation	---	nucleation	no	potential of low background, easily read, hard to shield	unavailable
0°C - 55°C operating limits	no	damage, microphonics	yes	easily read, few hazards	battery failure, microphonics, may need repair
---	---	---	yes	time-history enhances sensitivity	not commercially available